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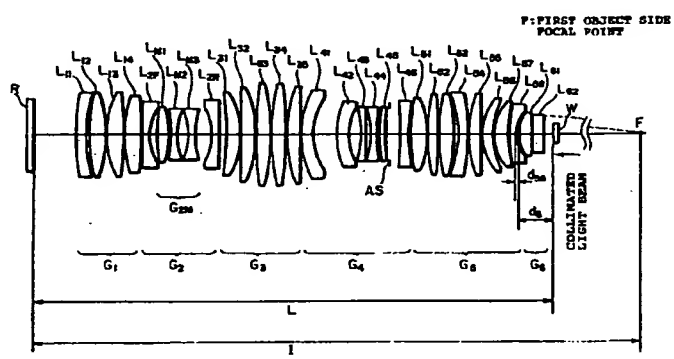
(54) Projection optical system and exposure apparatus using the same

(57) An exposure apparatus uses a projection optical system comprising a first lens Group G_1 with a positive refracting power, a second lens group G_2 with a negative refracting power, a third lens group G_3 with a positive refracting power, a fourth lens group G_4 with a negative refracting power, a fifth lens group G_5 with a positive refracting power, and a sixth lens group G_6 with a positive refracting power in order from the side of the first object R, wherein the second lens group G_2 comprises a front lens L_{2F} with a negative refracting power, a rear lens L_{2R} of a negative meniscus shape, and an intermediate lens group G_{2M} disposed between the front lens and the rear lens, and wherein the intermediate lens group G_{2M} has a first lens L_{M1} with a positive refracting power, a second lens L_{M2} with a negative refracting power, and a third lens L_{M3} with a negative refracting power in order from the side of the first object R. The system is arranged to satisfy within suitable ranges of focal lengths for the first to sixth lens groups G_1-G_6, based on the above arrangement.

Fig. 1



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Description

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to an exposure apparatus having a projection optical system for projecting a pattern of a first object onto a photosensitive substrate etc. as a second object, and more particularly to a projection optical system suitably applicable to projection exposure of a pattern for semiconductor or liquid crystal formed on a reticle (mask) as the first object onto the substrate (semiconductor wafer, plate, etc.) as the second object.

Related Background Art

As the patterns of integrated circuits become finer and finer, the resolving power required for the exposure apparatus used in printing of wafer also becomes higher and higher. In addition to the improvement in resolving power, the projection optical systems of the exposure apparatus are required to decrease image stress. In order to get ready for the finer tendency of transfer patterns, light sources for exposure have recently been changing from those emitting the light of exposure wavelength of the g-line (436 nm) to those emitting the light of exposure wavelength of the i-line (365 nm) that are mainly used at present. Further, a trend is to use light sources emitting shorter wavelengths, for example the excimer laser (KrF:248 nm, ArF:193 nm).

Here, the image stress includes those due to bowing etc. of the printed wafer on the image side of projection optical system and those due to bowing etc. of the reticle with circuit pattern etc. written therein, on the object side of projection optical system, as well as distortion caused by the projection optical system.

With a recent further progress of fineness tendency of transfer patterns, demands to decrease the image stress are also becoming harder.

Then, in order to decrease effects of the wafer bowing on the image stress, the conventional technology has employed the so-called image-side telecentric optical system that located the exit pupil position at a farther point on the image side of projection optical system.

On the other hand, the image stress due to the bowing of reticle can also be reduced by employing a so-called object-side telecentric optical system that locates the entrance pupil position of projection optical system at a farther point from the object plane, and there are suggestions to locate the entrance pupil position of projection optical system at a relatively far position from the object plane as described. Examples of those suggestions are described for example in Japanese Laid-open Patent Applications No. 63-118115 and No. 5-173065 and U.S.Patent No.5,260,832.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a high-performance projection optical system which can achieve the bitelecentricity in a compact design as securing a wide exposure area and a large numerical aperture and which can be well corrected for aberrations, particularly which can be very well corrected for distortion. The projection optical system can be applied to an exposure apparatus.

To achieve the above object, an exposure apparatus according to the present invention comprises at least a wafer stage allowing a photosensitive substrate to be held on a main surface thereof, an illumination optical system for emitting exposure light of a predetermined wavelength and transferring a predetermined pattern of a mask (reticle) onto the substrate, a projection optical system provided between a first surface on which the mask as a first object is disposed and a second surface on which a surface of the substrate as a second object is corresponded, for projecting an image of the pattern of the mask onto the substrate. The illumination optical system includes an alignment optical system for adjusting a relative positions between the mask and the wafer, and the mask is disposed on a reticle stage which is movable in parallel with respect to the main surface of the wafer stage. The projection optical system has a space permitting an aperture stop to be set therein. The photosensitive substrate comprises a wafer such as a silicon wafer or a glass plate, etc., and a photosensitive material such as a photoresist or the like coating a surface of the wafer. In particular, as shown in Fig. 1, the projection optical system includes a first lens group (G_1) with a positive refracting power, a second lens group (G_2) with a negative refracting power, a third lens group (G_3) with a positive refracting power, a fourth lens group (G_4) with a negative refracting power, a fifth lens group (G_5) with a positive refracting power, and a sixth lens group (G_6) with a positive refracting power in order from the side of the first object (for example, a mask).

The second lens group (G_2) comprises a front lens (L_{2F}) with a negative refracting power disposed as closest to the first object and shaped with a concave surface to the second object, a rear lens (L_{2R}) of a negative meniscus shape disposed as closest to the substrate and shaped with a concave surface to the mask, and an intermediate lens group (G_{2M}) disposed between the front lens (L_{2F}) and the rear lens (L_{2R}). In particular, the intermediate lens group (G_{2M}) has

a first lens (L_{M1}) with a positive refracting power, a second lens (L_{M2}) with a negative refracting power, and a third lens (L_{M3}) with a negative refracting power in order from the side of the first object.

Further, the projection optical system according to the present invention is arranged to satisfy the following conditions (1) to (6) when f_1 is a focal length of the first lens group (G_1), f_2 is a focal length of the second lens group (G_2), f_3 is a focal length of the third lens group (G_3), f_4 is a focal length of the fourth lens group (G_4), f_5 is a focal length of the fifth lens group (G_5), f_6 is a focal length of the sixth lens group (G_6), and L is a distance from the first object to the second object:

$$f_1/L < 0.8 \quad (1)$$

$$-0.033 < f_2/L \quad (2)$$

$$0.01 < f_3/L < 1.0 \quad (3)$$

$$f_4/L < -0.005 \quad (4)$$

$$0.01 < f_5/L < 0.9 \quad (5)$$

$$0.02 < f_6/L < 1.6. \quad (6)$$

The projection optical system is so arranged as to have at least the first lens group (G_1) with positive refracting power, the second lens group (G_2) with negative refracting power, the third lens group (G_3) with positive refracting power, the fourth lens group (G_4) with negative refracting power, the fifth lens group (G_5) with positive refracting power, and the sixth lens group (G_6) with positive refracting power in the named order from the first object side.

First, the first lens group (G_1) with positive refracting power contributes mainly to a correction of distortion while maintaining telecentricity, and specifically, the first lens group (G_1) is arranged to generate a positive distortion to correct in a good balance negative distortions caused by the plurality of lens groups located on the second object side after the first lens group (G_1). The second lens group (G_2) with negative refracting power and the fourth lens group (G_4) with negative refracting power contribute mainly to a correction of Petzval sum to make the image plane flat. The two lens groups of the second lens group (G_2) with negative refracting power and the third lens group (G_3) with positive refracting power form an inverse telescopic system to contribute to guarantee of back focus (a distance from an optical surface such as a lens surface closest to the second object in the projection optical system to the second object) in the projection optical system. The fifth lens group (G_5) with positive refracting power and the sixth lens group (G_6) similarly with positive refracting power contribute mainly to suppressing generation of distortion and suppressing generation particularly of spherical aberration as much as possible in order to fully support high NA structure on the second object side.

Based on the above arrangement, the front lens (L_{2F}) with the negative refracting power disposed as closest to the first object in the second lens group (G_2) and shaped with the concave surface to the second object contributes to correction for curvature of field and coma, and the rear lens (L_{2R}) of the negative meniscus shape disposed as closest to the second object in the second lens group (G_2) and shaped with the concave surface to the first object contributes mainly to correction for coma. The rear lens (L_{2R}) also contributes to correction for curvature of field. Further, in the intermediate lens group (G_{2M}) disposed between the front lens (L_{2F}) and the rear lens (L_{2R}), the first lens (L_{M1}) with the positive refracting power contributes to correction for negative distortion generated by the second lens (L_{M2}) and third lens (L_{M3}) of the negative refracting powers greatly contributing to correction for curvature of field.

Condition (1) defines an optimum ratio between the focal length f_1 of the first lens group (G_1) with the positive refracting power and the distance (object-to-image distance) L from the first object (reticle etc.) to the second object (wafer etc.). This condition (1) is mainly for well-balanced correction for distortion.

Above the upper limit of condition (1), large negative distortion will appear. In order to achieve a compact design as securing a reduction magnification and a wide exposure area and to achieve good correction for distortion, the upper limit of condition (1) is preferably set to 0.14, as $f_1/L < 0.14$. In order to suppress appearance of spherical aberration of pupil, the lower limit of condition (1) is preferably set to 0.02, as $0.02 < f_1/L$.

Condition (2) defines an optimum ratio between the focal length f_2 of the second lens group (G_2) with the negative refracting power and the distance (object-to-image distance) L from the first object (reticle etc.) to the second object (wafer etc.). This condition (2) is a condition for achieving a compact design as securing a wide exposure region and achieving good correction for Petzval sum.

Here, below the lower limit of condition (2), it becomes difficult to achieve the compact design as securing the wide exposure region and positive Petzval sum will appear, thus not preferred. In order to achieve further compact design or superior correction for Petzval sum, the lower limit of condition (2) is preferably set to -0.032, as $-0.032 < f_2/L$. In order to suppress appearance of negative distortion, the upper limit of condition (2) is preferably set to -0.005, as $f_2/L < -0.005$.

Condition (3) defines an optimum ratio between the focal length f_3 of the third lens group (G_3) with the positive refracting power and the distance (object-to-image distance) L from the first object (reticle etc.) to the second object

(wafer etc.). Here, below the lower limit of condition (3), the refractive power of the second lens group (G_2) or the fourth lens group (G_4) becomes too strong, resulting in giving rise to negative distortion and coma in the second lens group (G_2) or giving rise to coma in the fourth lens group (G_4). On the other hand, above the upper limit of condition (3), the refractive power of the second lens group (G_2) or the fourth lens group (G_4) becomes too weak, failing to well correct Petzval sum.

Condition (4) defines an optimum ratio between the focal length f_4 of the fourth lens group (G_4) with the negative refracting power and the distance (object-to-image distance) L from the first object (reticle etc.) to the second object (wafer etc.).

Here, above the upper limit of condition (4), coma will appear, thus not preferred. Further, in order to suppress appearance of coma, the upper limit of condition (4) is preferably set to -0.047, as $f_4/L < -0.047$.

In order to well correct spherical aberration, the lower limit of condition (4) is preferably set to - 0.098, as $-0.098 < f_4/L$.

Condition (5) defines an optimum ratio between the focal length f_5 of the fifth lens group (G_5) with the positive refracting power and the distance (object-to-image distance) L from the first object (reticle etc.) to the second object (wafer etc.). This condition (5) is for achieving well-balanced correction for spherical aberration, distortion, and Petzval sum as maintaining a large numerical aperture. Below the lower limit of this condition (5), the refracting power of the fifth lens group (G_5) becomes too strong, resulting in giving rise to great negative spherical aberration in addition to negative distortion in the fifth lens group (G_5). Above the upper limit of this condition (5), the refracting power of the fifth lens group (G_5) becomes too weak, which inevitably weakens the refracting power of the fourth lens group (G_4) with the negative refracting power. As a consequence, Petzval sum will not be well corrected.

Condition (6) defines an optimum ratio between the focal length f_6 of the sixth lens group (G_6) with the positive refracting power and the distance (object-to-image distance) L from the first object (reticle etc.) to the second object (wafer etc.). This condition (6) is for suppressing appearance of higher-order spherical aberration and negative distortion as maintaining a large numerical aperture. Below the lower limit of this condition (6), the sixth lens group (G_6) itself gives rise to great negative distortion; above the upper limit of this condition (6), higher-order spherical aberration will appear.

On the basis of the above composition it is preferred that when I is an axial distance from the first object to a first-object-side focal point F of the entire projection optical system and L is the distance from the first object to the second object, the following condition be satisfied:

$$1.0 < I/L \qquad (7)$$

The condition (7) defines an optimum ratio between the axial distance I from the first object to the first-object-side focal point F of the entire projection optical system and the distance (object-image distance) L from the first object (reticle etc.) to the second object (wafer etc.). Here, the first-object-side focal point F of the entire projection optical system means an intersecting point of outgoing light from the projection optical system with the optical axis after collimated light beams are let to enter the projection optical system on the second object side in the paraxial region with respect to the optical axis of the projection optical system and when the light beams in the paraxial region are outgoing from the projection optical system.

Below the lower limit of this condition (7) the first-object-side telecentricity of the projection optical system will become considerably destroyed, so that changes of magnification and distortion due to an axial deviation of the first object will become large. As a result, it becomes difficult to faithfully project an image of the first object at a desired magnification onto the second object. In order to fully suppress the changes of magnification and distortion due to the axial deviation of the first object, the lower limit of the above condition (7) is preferably set to 1.7, i.e., $1.7 < I/L$. Further, in order to correct a spherical aberration and a distortion of the pupil both in a good balance while maintaining the compact design of the projection optical system, the upper limit of the above condition (7) is preferably set to 6.8, i.e., $I/L < 6.8$.

It is also preferred that the fourth lens group (G_4) have a front lens group disposed as closest to the first object and a rear lens group disposed as closest to the second object, that an intermediate lens group having a first negative lens (L_{43}) and a second negative lens (L_{44}) in order from the side of the first object be disposed between the front lens group in the fourth lens group (G_4) and the rear lens group in the fourth lens group (G_4), that the front lens group have two negative meniscus lenses (L_{41}, L_{42}) each shaped with a concave surface to the second object, that the rear lens group has a negative lens (L_{46}) with a concave surface to the first object, and that when f_{4A} is a focal length of the first negative lens (L_{43}) in the fourth lens group (G_4) and f_{4B} is a focal length of the second negative lens (L_{44}) in the fourth lens group (G_4), the following condition be satisfied:

$$0.05 < f_{4A}/f_{4B} < 20. \qquad (8)$$

Below the lower limit of condition (8), the refractive power of the first negative lens (L_{43}) becomes strong relative to the refractive power of the second negative lens (L_{44}), so that the first negative lens (L_{43}) will give rise to higher-order spherical aberration and higher-order coma. In order to suppress appearance of the higher-order spherical aberration

and higher-order coma, the lower limit of the above condition (8) is preferably set to 0.1, as $0.1 < f_{4A}/f_{4B}$. On the other hand, above the upper limit of condition (8), the refracting power of the second negative lens (L_{44}) becomes strong relative to the refracting power of the first negative lens (L_{43}), so that the second negative lens (L_{44}) will give rise to higher-order spherical aberration and higher-order coma. In order to further suppress appearance of higher-order spherical aberration and higher-order coma, the upper limit of the above condition (8) is preferably set to 10, as $f_{4A}/f_{4B} < 10$.

It is also preferred that when r_{2Ff} is a radius of curvature of a first-object-side surface of the front lens (L_{2F}) and r_{2Fr} is a radius of curvature of a second-object-side surface of the front lens (L_{2F}), the front lens (L_{2F}) in the second lens group (G_2) satisfy the following condition:

$$1.00 \leqq (r_{2Ff} - r_{2Fr})/(r_{2Ff} + r_{2Fr}) < 5.0. \tag{9}$$

Below the lower limit of this condition (9), sufficient correction for spherical aberration of pupil becomes impossible, thus not preferred. On the other hand, above the upper limit of this condition (9), coma will appear, thus not preferred.

It is also preferred that the fourth lens group (G_4) have a front lens group having a negative lens (L_{41}) disposed as closest to the first object and shaped with a concave surface to the second object, and a rear lens group having a negative lens (L_{46}) disposed as closest to the second object and shaped with a concave surface to the first object, that an intermediate lens group having at least a negative lens (L_{44}) and a positive lens (L_{45}) with a convex surface adjacent to a concave surface of the negative lens (L_{44}) be disposed between the front lens group in the fourth lens group (G_4) and the rear lens group in the fourth lens group (G_4), and that when r_{4N} is a radius of curvature of the concave surface of the negative lens (L_{44}) in the intermediate lens group and r_{4P} is a radius of curvature of the convex surface of the positive lens (L_{45}) in the intermediate lens group, the following condition be satisfied:

$$-0.9 < (r_{4N} - r_{4P})/(r_{4N} + r_{4P}) < 0.9, \tag{10}$$

provided that when L is the distance from the first object to the second object, the concave surface of the negative lens (L_{44}) in the intermediate lens group or the convex surface of the positive lens (L_{45}) in the intermediate lens group satisfies at least one of the following conditions:

$$|r_{4N}/L| < 2.0 \tag{11}$$

$$|r_{4P}/L| < 2.0. \tag{12}$$

Conditions (10) to (12) define an optimum configuration of a gas lens formed by the concave surface of the negative lens (L_{44}) in the intermediate lens group and the convex surface of the positive lens (L_{45}) in the intermediate lens group. When condition (11) or (12) is satisfied, this gas lens can correct higher-order spherical aberration. For further correction of higher-order spherical aberration, the upper limits of condition (11) and condition (12) are preferably set to 0.8, as $|r_{4N}/L| < 0.8$ and $|r_{4P}/L| < 0.8$. Here, above the upper limit or below the lower limit of condition (10), coma will appear, thus not preferred. If neither condition (11) nor condition (12) is satisfied, correction for higher-order spherical aberration is impossible even if condition (10) is satisfied, thus not preferred.

It is also preferred that when f_{22} is a focal length of the second lens (L_{M2}) with the negative refracting power in the second lens group (G_2) and f_{23} is a focal length of the third lens (L_{M3}) with the negative refracting power in the second lens group (G_2), the following condition be satisfied:

$$0.1 < f_{22}/f_{23} < 10. \tag{13}$$

Below the lower limit of the condition (13) the refracting power of the second negative lens (L_{M2}) becomes strong relative to the refracting power of the third negative lens (L_{M3}), so that the second negative lens (L_{M2}) generates a large coma and a large negative distortion. In order to correct the negative distortion in a better balance, the lower limit of the above condition (13) is preferably set to 0.7, i.e., $0.7 < f_{22}/f_{23}$. Above the upper limit of this condition (13) the refracting power of the third negative lens (L_{M3}) becomes strong relative to the refracting power of the second negative lens (L_{M2}), so that the third negative lens generates a large coma and a large negative distortion. In order to correct the negative distortion in a better balance while well correcting the coma, the upper limit of the above condition (13) is preferably set to 1.5, i.e., $f_{24}/f_{23} < 1.5$.

It is also preferred that the fifth lens group (G_5) have a negative meniscus lens (for example, L_{54}), and a positive lens (for example, L_{53}) disposed as adjacent to a concave surface of the negative meniscus lens and having a convex surface opposed to the concave surface of the negative meniscus lens and that when r_{5n} is a radius of curvature of the concave surface of the negative meniscus lens in the fifth lens group (G_5) and r_{5P} is a radius of curvature of the convex surface, opposed to the concave surface of the negative meniscus lens, of the positive lens disposed as adjacent to the concave surface of the negative meniscus lens in the fifth lens group (G_5), the following condition be satisfied:

$$0 < (r_{5P} - r_{5n})/(r_{5P} + r_{5n}) < 1. \quad (14)$$

In this case, it is preferred that the negative meniscus lens (for example, L_{54}) and the positive lens (L_{53}) adjacent to the concave surface of the negative meniscus lens be disposed between at least one positive lens (for example, L_{52}) in the fifth lens group G_5 and at least one positive lens (for example, L_{55}) in the fifth lens group (G_5).

In this case, in order to suppress the negative distortion without generating the higher-order spherical aberrations in the lens (L_{61}) located closest to the first object in the sixth lens group (G_6), it is desirable that the lens surface closest to the first object have a shape with a convex surface to the first object and that the following condition be satisfied when a radius of curvature on the second object side, of the negative lens (L_{58}) placed as closest to the second object in the fifth lens group (G_5) is r_{5R} and a radius of curvature on the first object side, of the lens (L_{61}) placed as closest to the first object in the sixth lens group (G_6) is r_{6F}.

$$-0.90 < (r_{5R} - r_{6F})/(r_{5R} + r_{6F}) < -0.001 \quad (15)$$

This condition (15) defines an optimum shape of a gas lens formed between the fifth lens group (G_5) and the sixth lens group (G_6). Below the lower limit of this condition (15) a curvature of the second-object-side concave surface of the negative lens (L_{58}) located closest to the second object in the fifth lens group (G_5) becomes too strong, thereby generating higher-order comas. Above the upper limit of this condition (15) refracting power of the gas lens itself formed between the fifth lens group (G_5) and the sixth lens group (G_6) becomes weak, so that a quantity of the positive distortion generated by this gas lens becomes small, which makes it difficult to well correct a negative distortion generated by the positive lens in the fifth lens group (G_5). In order to fully suppress the generation of higher-order comas, the lower limit of the above condition (15) is preferably set to -0.30, i.e., $-0.30 < (r_{5R} - r_{6F})/(r_{5R} + r_{6F})$.

Also, it is further preferable that the following condition be satisfied when a lens group separation between the fifth lens group (G_5) and the sixth lens group (G_6) is d_{56} and the distance from the first object to the second object is L

$$d_{56}/L < 0.017 \quad (16)$$

Above the upper limit of this condition (16), the lens group separation between the fifth lens group (G_5) and the sixth lens group (G_6) becomes too large, so that a quantity of the positive distortion generated becomes small. As a result, it becomes difficult to correct the negative distortion generated by the positive lens in the fifth lens group (G_5) in a good balance.

Also, it is more preferable that the following condition be satisfied when a radius of curvature of the lens surface closest to the first object in the sixth lens group (G_6) is r_{6F} and an axial distance from the lens surface closest to the first object in the sixth lens group (G_6) to the second object is d_6.

$$0.50 < d_6/r_{6F} < 1.50 \quad (17)$$

Below the lower limit of this condition (17), the positive refracting power of the lens surface closest to the first object in the sixth lens group (G_6) becomes too strong, so that a large negative distortion and a large coma are generated. Above the upper limit of this condition (17), the positive refracting power of the lens surface closest to the first object in the sixth lens group (G_6) becomes too weak, thus generating a large coma. In order to further suppress the generation of coma, the lower limit of the condition (17) is preferably set to 0.84, i.e., $0.84 < d_6/r_{6F}$.

Also, it is to be more desired that said fifth lens group (G_5) have a negative lens (L_{58}) placed as closest to the second object and having a concave surface opposed to the second object and that the following condition be satisfied when a radius of curvature on the first object side in the negative lens (L_{58}) closest to the second object in said fifth lens group (G_5) is r_{5F} and a radius of curvature on the second object side in the negative lens (L_{58}) closest to the second object in said fifth lens group (G_5) is r_{5R}:

$$0.30 < (r_{5F} - r_{5R})/(r_{5F} + + r_{5R}) < 1.28. \quad (18)$$

Below the lower limit of this condition (18), it becomes difficult to correct both the Petzval sum and the coma; above the upper limit of this condition (18), large higher-order comas appear, which is not preferable. In order to further prevent the generation of higher-order comas, the upper limit of the condition (18) is preferably set to 0.93, i.e., $(r_{5F} - r_{5R})/(r_{5F} + r_{5R}) < 0.93$.

It is more desired that when f_{21} is a focal length of the first lens (L_{M1}) with the positive refracting power in the intermediate lens group (G_{2M}) in the second lens group (G_2) and L is the distance from the first object to the second object, the following condition be satisfied:

$$0.230 < f_{21}/L < 0.40. \quad (19)$$

Below the lower limit of condition (19), positive distortion will appear; above the upper limit of condition (19), negative distortion will appear, either of which is thus not preferred. Further, in order to further correct the negative distortion, the second-object-side lens surface of the first lens (L_{M1}) is preferably formed in a lens configuration shaped with a convex surface facing the second object.

It is also preferred that when f_{2F} is a focal length of the front lens (L_{2F}) with the negative refracting power disposed as closest to the first object in the second lens group (G_2) and shaped with the concave surface to the second object and f_{2R} is a focal length of the rear lens (L_{2R}) with the negative refracting power disposed as closest to the second object in the second lens group (G_2) and shaped with the concave surface to the first object, the following condition be satisfied:

$$0 \leq f_{2F}/f_{2R} < 18. \tag{20}$$

Also, the front lens (L_{2F}) and the rear lens (L_{2R}) in the second lens group (G_2) preferably satisfy the following condition when the focal length of the front lens (L_{2F}) placed as closest to the first object in the second lens group (G_2) and having the negative refracting power with a concave surface to the second object is f_{2F} and the focal length of the rear lens (L_{2R}) placed as closest to the second object in the second lens group (G_2) and having the negative refracting power with a concave surface to the second object is f_{2R}.

$$0 \leq f_{2F}/f_{2R} < 18 \tag{20}$$

The condition (20) defines an optimum ratio between the focal length f_{2R} of the rear lens (L_{2R}) in the second lens group (G_2) and the focal length f_{2F} of the front lens (L_{2F}) in the second lens group (G_2). Below the lower limit and above the upper limit of this condition (20), a balance is destroyed for refracting power of the first lens group (G_1) or the third lens group (G_3), which makes it difficult to correct the distortion well or to correct the Petzval sum and the astigmatism simultaneously well.

In order to further well correct Petzval sum, the intermediate lens group (G_{2M}) in the second lens group (G_2) preferably has a negative refracting power.

For the above lens groups to achieve satisfactory aberration correction functions, specifically, they are desired to be constructed in the following arrangements.

First, for the first lens group (G_1) to have a function to suppress appearance of higher-order distortion and appearance of spherical aberration of pupil, the first lens group (G_1) preferably has at least two positive lenses; for the third lens group (G_3) to have a function to suppress degradation of spherical aberration and Petzval sum, the third lens group (G_3) preferably has at least three positive lenses; further, for the fourth lens group (G_4) to have a function to suppress appearance of coma as correcting Petzval sum, the fourth lens group (G_4) preferably has at least three negative lenses. For the fifth lens group (G_5) to have a function to suppress appearance of negative distortion and spherical aberration, the fifth lens group (G_5) preferably has at least five positive lenses; further, for the fifth lens group (G_5) to have a function to correct negative distortion and Petzval sum, the fifth lens group (G_5) preferably has at least one negative lens. For the sixth lens group (G_6) to effect focus on the second object so as not to give rise to large spherical aberration, the sixth lens group (G_6) preferably has at least one positive lens.

For further compact design, the intermediate lens group in the second lens group desirably comprises only two negative lenses.

For the sixth lens group (G_6) to have a function to further suppress appearance of negative distortion, the sixth lens group (G_6) is preferably arranged to comprise three or less lenses including at least one lens surface satisfying the following condition (21).

$$1/|\Phi L| < 20 \tag{21}$$

where Φ: a refractive power of the lens surface; and
L: the distance (object-to-image distance) from the first object to the second object.

The refractive power of lens surface, stated here, is given by the following equation where r is a radius of curvature of the lens surface, n_1 a refractive index of a medium on the first object side of the lens surface, and n_2 a refractive index of a medium on the second object side of the lens surface.

$$\Phi = (n_2 - n_1)/r$$

Here, if there are four or more lenses having the lens surface satisfying this condition (21), the number of lens surfaces with some curvature, located near the second object, becomes increased, which generates the distortion, thus not preferable.

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not to be considered as limiting the present invention.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art form this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a drawing to show parameters defined in embodiments of the present invention.

Fig. 2 is a drawing to show schematic structure of an exposure apparatus to which the projection optical system according to the present invention is applied.

Fig. 3 is a lens arrangement drawing of the projection optical system in the first embodiment according to the present invention.

Fig. 4 is a lens arrangement drawing of the projection optical system in the second embodiment according to the present invention.

Fig. 5 is a lens arrangement drawing of the projection optical system in the third embodiment according to the present invention.

Fig. 6 is a lens arrangement drawing of the projection optical system in the fourth embodiment according to the present invention.

Figs. 7-10 are aberration diagrams to show aberrations in the projection optical system of the first embodiment.

Figs. 11-14 are aberration diagrams to show aberrations in the projection optical system of the second embodiment.

Figs. 15-18 are aberration diagrams to show aberrations in the projection optical system of the third embodiment.

Figs. 19-22 are aberration diagrams to show aberrations in the projection optical system of the fourth embodiment.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Various embodiments of the projection optical system according to the present invention will be described with reference to the drawings. In the examples, the present invention is applied to the projection optical system in the projection exposure apparatus for projecting an image of patterns of reticle onto a wafer coated with a photoresist. Fig. 2 shows a basic structure of the exposure apparatus according to the present invention. As shown in Fig. 2, an exposure apparatus of the present invention comprises at least a wafer stage 3 allowing a photosensitive substrate W to be held on a main surface 3a thereof, an illumination optical system 1 for emitting exposure light of a predetermined wavelength and transferring a predetermined pattern of a mask (reticle R) onto the substrate W, a light source 100 for supplying an exposure light to the illumination optical system 1, a projection optical system 5 provided between a first surface P1 (object plane) on which the mask R is disposed and a second surface P2 (image plane) to which a surface of the substrate W is corresponded, for projecting an image of the pattern of the mask R onto the substrate W. The illumination optical system 1 includes an alignment optical system 110 for adjusting a relative positions between the mask R and the wafer W, and the mask R is disposed on a reticle stage 2 which is movable in parallel with respect to the main surface of the wafer stage 3. A reticle exchange system 200 conveys and changes a reticle (mask R) to be set on the reticle stage 2. The reticle exchange system 200 includes a stage driver for moving the reticle stage 2 in parallel with respect to the main surface 3a of the wafer stage 3. The projection optical system 5 has a space permitting an aperture stop 6 to be set therein. The sensitive substrate W comprises a wafer 8 such as a silicon wafer or a glass plate, etc., and a photosensitive material 7 such as a photoresist or the like coating a surface of the wafer 8. The wafer stage 3 is moved in parallel with respect to a object plane P1 by a stage control system 300. Further, since a main control section 400 such as a computer system controls the light source 100, the reticle exchange system 200, the stage control system 300 or the like, the exposure apparatus can perform a harmonious action as a whole.

The techniques relating to an exposure apparatus of the present invention are described, for example, in United States Patent Applications No. 255,927, No. 260,398, No. 299,305, United States Patents No. 4,497,015, No. 4,666,273, No. 5,194,893, No. 5,253,110, No. 5,333,035, No. 5,365,051, No. 5,379,091, or the like. The reference of United States Patent Application No. 255,927 teaches an illumination optical system (using a laser source) applied to a scan type exposure apparatus. The reference of United States Patent Application No. 260,398 teaches an illumination optical system (using a lamp source) applied to a scan type exposure apparatus. The reference of United States Patent Application No. 299,305 teaches an alignment optical system applied to a scan type exposure apparatus. The reference of United States Patent No. 4,497,015 teaches an illumination optical system (using a lamp source) applied to a scan type exposure apparatus. The reference of United States Patent No. 4,666,273 teaches a step-and repeat type exposure apparatus capable of using the projection optical system of the present invention. The reference of United States Patent No. 5,194,893 teaches an illumination optical system, an illumination region, mask-side and reticle-side interferometers,

a focusing optical system, alignment optical system, or the like. The reference of United States Patent No. 5,253,110 teaches an illumination optical system (using a laser source) applied to a step-and-repeat type exposure apparatus. The '110 reference can be applied to a scan type exposure apparatus. The reference of United States Patent No. 5,333,035 teaches an application of an illumination optical system applied to an exposure apparatus. The reference of United States Patent No. 5,365,051 teaches a auto-focusing system applied to an exposure apparatus. The reference of United States Patent No. 5,379,091 teaches an illumination optical system (using a laser source) applied to a scan type exposure apparatus.

As described above, a reticle R (first object) as a projection mask with specific circuit patterns formed therein is disposed on the object plane (P1) of the projection optical system 1 and a wafer W (second object) as a substrate on the image plane (P2) of the projection optical system 1. Here, the reticle R is held on a reticle stage 2 and the wafer W on a wafer stage 3 arranged as movable on a two-dimensional basis. Disposed above the reticle R is an illumination optical system 1 for uniformly illuminating the reticle R.

In the above arrangement, light supplied from the light source 100 through the illumination optical system 1 illuminates the reticle R to form an image at the pupil position of the projection optical system 1 (the position of aperture stop 6). Namely, the illumination optical system 1 uniformly illuminates the reticle R under Köhler illumination. Then the pattern image of reticle R illuminated under Köhler illumination is projected (or transferred) onto the wafer W.

The present embodiment shows an example of which the light source 100 is a mercury lamp for supplying the i-line (365 nm). The structure of the projection optical system in each embodiment will be described by reference to Fig. 3 to Fig. 6. Fig. 3 to Fig. 6 are lens structural drawings of the projection optical systems 1 in the first to fourth embodiments, respectively, according to the present invention.

As shown in Fig. 3 to Fig. 6, the projection optical system 1 in each embodiment has a first lens group G_1 with a positive refractive power, a second lens group G_2 with a negative refractive power, a third lens group G_3 with a positive refractive power, a fourth lens group G_4 with a negative refractive power, a fifth lens group G_5 with a positive refractive power, and a sixth lens unit G_6 with a positive refractive power in order from the side of reticle R as a first object, is arranged as substantially telecentric on the object side (reticle R side) and on the image side (wafer W side), and has a reduction magnification.

In the projection optical system 1 in each of the embodiments shown in Fig. 3 to Fig. 6, an object-to-image distance (a distance along the optical axis from the object plane to the image plane, or a distance along the optical axis from the reticle R to wafer W) L is 1100, an image-side numerical aperture NA is 0.57, a projection magnification β is 1/5, and a diameter of an exposure area on the wafer W is 31.2. The object-to-image distance L and the diameter of the exposure area are expressed in a same unit, and the unit corresponds to a unit of r and d shown in the following talbes 1, 3, 5 and 7.

First described is a specific lens arrangement of the first embodiment shown in Fig. 3. The first lens group G_1 has a negative meniscus lens L_{11} shaped with a concave surface to the image, a positive lens (positive lens of a biconvex shape) L_{12} shaped with a convex surface to the object, and two positive lenses (positive lenses of biconvex shapes) L_{13}, L_{14} each shaped with a strong-curvature surface to the object in order from the object side.

Further, the second lens group G_2 has a negative lens (negative lens of a biconcave shape: front lens) L_{2F} disposed as closest to the object and shaped with a concave surface to the image, a negative meniscus lens (rear lens) L_{2R} disposed as closest to the image and shaped with a concave surface to the object, and an intermediate lens group G_{2M} with a negative refractive power disposed between these negative lens L_{2F} and negative lens L_{2R}. This intermediate lens group G_{2M} has a positive lens (positive lens of a biconvex shape: first lens) L_{M1} shaped with a strong-curvature surface to the image, a negative lens (negative lens of a biconcave shape: second lens) L_{M2} shaped with a strong-curvature surface to the image, and a negative lens (negative lens of a biconcave shape: third lens) L_{M3} shaped with a strong-curvature surface to the object in order from the object side.

The third lens group G_3 has two positive lenses (positive meniscus lenses) L_{31}, L_{32} each shaped with a strong-curvature surface to the image, a positive lens L_{33} of a biconvex shape, a positive lens (positive lens of a biconvex shape) L_{34} shaped with a strong-curvature surface to the object, and a positive lens (positive meniscus lens) L_{35} shaped with a strong-curvature surface to the object in order from the object side.

The fourth lens group G_4 has two negative meniscus lenses (front lens group) L_{41}, L_{42} each shaped with a concave surface to the image, a negative lens (negative meniscus lens: first negative lens) L_{43} shaped with a concave surface to the object, a negative lens (second negative lens: negative lens with a concave surface to the image) L_{44} of a biconcave shape, a positive lens (positive meniscus lens: positive lens having a convex surface adjacent to the concave surface of the negative lens L_{44}) L_{45} shaped with a convex surface to the object, and a negative lens (negative lens of a biconcave shape: rear lens group) L_{46} shaped with a concave surface to the object in order from the object side.

The fifth lens group G_5 has two positive lenses (positive lenses of biconvex shapes) L_{51}, L_{52} each shaped with a convex surface to the image, a positive lens L_{53} of a biconvex shape, a negative meniscus lens L_{54} shaped with a concave surface to the object, a positive lens L_{55} shaped with a stronger-curvature surface to the object, two positive lenses (positive meniscus lenses) L_{56}, L_{57} each shaped with a stronger-curvature surface to the object, and a negative meniscus lens L_{58} shaped with a concave surface to the image in order from the object side.

Further, the sixth lens group G_6 is composed of a positive lens (positive lens of a biconvex shape) L_{61} shaped with a stronger-curvature surface to the object, and a negative lens (negative lens of a biconcave shape) L_{62} shaped with a concave surface to the object in order from the object side.

In the present embodiment, an aperture stop 6 is disposed between the positive meniscus lens L_{45} with the convex surface to the object and the negative lens L_{46} of the biconcave shape, that is, between the intermediate lens group in the fourth lens group G_4 and the rear lens group in the fourth lens group G_4.

In the first lens group G_1 in the present embodiment, the concave surface of the negative meniscus lens L_{11} with the concave surface to the image and the object-side lens surface of the positive biconvex lens L_{12} have nearly equal curvatures and are arranged as relatively close to each other, and these two lens surfaces correct higher-order distortion.

Since the first lens L_{M1} with the positive refractive power in the second lens group G_{2M} is constructed in the biconvex shape with the convex surface to the image and also with the other convex surface to the object, it can suppress appearance of spherical aberration of pupil.

Since the fourth lens group G_4 is so arranged that the negative meniscus lens L_{41} with the concave surface to the image is disposed on the object side of the negative lens (negative biconcave lens) L_{44} and that the negative lens L_{46} with the concave surface to the object is disposed on the image side of the negative lens (negative biconcave lens) L_{44}, it can correct Petzval sum as suppressing appearance of coma.

Since in the first embodiment the aperture stop 6 is placed between the image-side concave surface of the negative meniscus lens L_{41} and the object-side concave surface of the negative lens L_{46} in the fourth lens group G_4, the lens groups of from the third lend group G_3 to the sixth lens group G_6 can be arranged around the aperture stop 6 with a more or less reduction magnification and without destroying the symmetry too much, thus enabling to suppress asymmetric aberration, particularly coma and distortion. Since the positive lens L_{53} in the fifth lens group G_5 has a convex surface opposed to the negative meniscus lens L_{54} and the other lens surface on the opposite side to the negative meniscus lens L_{54} is also a convex surface, higher-order spherical aberration can be prevented from appearing with an increase of numerical aperture.

The specific lens arrangement of the second embodiment shown in Fig. 4 is similar to that of the first embodiment as shown in Fig. 3 and described above. The third lens group G_3 in the second embodiment is different from that in the first embodiment in that the third lens group G_3 is composed of two positive lenses (positive meniscus lenses) L_{31}, L_{32} each shaped with a strong-curvature surface to the image, a positive lens L_{33} of a biconvex shape, a positive lens (positive lens of a biconvex shape) L_{34} shaped with a strong-curvature surface to the object, and a positive lens (positive lens of a biconvex shape) L_{35} shaped with a strong-curvature surface to the object in order from the object side.

In the second embodiment, the fourth lens group G_4 is different from that in the first embodiment in that the fourth lens group G_4 is composed of two negative meniscus lenses (front lens group) L_{41}, L_{42} each shaped with a concave surface to the image, a negative lens (negative lens of a biconcave shape: first negative lens) L_{43} shaped with a concave surface to the object, a negative lens (second negative lens: negative lens with a concave surface to the image) L_{44} of a biconcave shape, a positive lens (positive meniscus lens: positive lens having a convex surface adjacent to the concave surface of the negative lens L_{44}) L_{45} shaped with a convex surface to the object, and a negative lens (negative lens of a biconcave shape: rear lens group) L_{46} shaped with a stronger concave surface to the object in order from the object side, but the function thereof is the same as that in the first embodiment as described above.

Further, the first and second lens groups G_1, G_2 and the fifth and sixth lens groups G_5, G_6 in the second embodiment achieve the same functions as those in the first embodiment as described above.

The specific lens arrangement of the third embodiment shown in Fig. 5 is similar to that of the first embodiment shown in Fig. 3 and described previously. The first lens group G_1 of the present embodiment is different from that of the first embodiment in that the first lens group G_1 is composed of a negative meniscus lens L_{11} shaped with a concave surface to the image, a positive lens (positive lens of a biconvex shape) L_{12} shaped with a convex surface to the object, a positive lens (positive lens of a plano-convex shape) L_{13} shaped with a strong-curvature surface to the object, and a positive lens (positive lens of a biconvex shape) L_{14} shaped with a strong-curvature surface to the object in order from the object side, but the function thereof is the same as that in the first embodiment as described previously.

The second to sixth lens groups G_2-G_6 in the third embodiment achieve the same functions as those in the first embodiment as described previously.

The specific lens arrangement of the fourth embodiment of Fig. 6 is similar to that of the first embodiment shown in Fig. 3 and described previously. The fourth lens group G_4 in the present embodiment is different from that of the first embodiment in that the fourth lens group G_4 is composed of two negative meniscus lenses (front lens group) L_{41}, L_{42} each with a concave surface to the image, a negative lens (negative lens of a biconcave shape: first negative lens) L_{43} shaped with a concave surface to the object, a negative lens (second negative lens: negative lens with a concave surface to the image) L_{44} of a biconcave shape, a positive lens (positive meniscus lens: a positive lens having a convex surface adjacent to the concave surface of the negative lens L_{44}) L_{45} shaped with a convex surface to the object, and a negative lens (negative lens of a biconcave shape: rear lens group) L_{46} shaped with a concave surface to the object in order from the object side, but the function thereof is the same as that in the first embodiment as described previously.

Further, in the fourth embodiment, the sixth lens group G_6 is different from that of the first embodiment in that the sixth lens group G_6 is composed of a positive lens (positive lens of a biconvex shape) L_{61} shaped with a stronger-curvature surface to the object and a negative lens (negative meniscus lens) L_{62} shaped with a concave surface to the object in order from the object side.

The first to third lens groups G_1 to G_3 and the fifth lens group G_5 in the present embodiment achieve the same functions as those in the first embodiment described previously.

Table 1 to Table 8 to follow list values of specifications and correspondent values to the conditions for the respective embodiments in the present invention.

In the tables, left-end numerals represent orders from the object side (reticle R side), r radii of curvatures of lens surfaces, d separations between lens surfaces, n refractive indices of glass materials for exposure wavelength λ of 365 nm, d_0 the distance along the optical axis from the first object (reticle R) to the lens surface (first lens surface) closest to the object (reticle R) in the first lens group G_1, β the projection magnification of projection optical system, Bf the distance along the optical axis from the lens surface closest to the image (wafer W) in the sixth lens group G_6 to the image plane P2 (wafer W plane), NA the numerical aperture on the image side (wafer W side), of projection optical system, and L is the object-to-image distance from the object plane P1 (reticle R plane) to the image plane P2 (wafer W plane). Further, in the tables, f_1 represents the focal length of the first lens group G_1, f_2 the focal length of the second lens group G_2, f_3 the focal length of the third lens group G_3, f_4 the focal length of the fourth lens group G_4, f_5 the focal length of the fifth lens group G_5, f_6 the focal length of the sixth lens group G_6, L the distance (object-to-image distance) from the object plane (reticle plane) to the image plane (wafer plane), I the axial distance from the first object (reticle) to the first-object-side focal point F of the entire projection optical system (provided that the first-object-side focal point F of the entire projection optical system means an intersecting point of emergent light with the optical axis when parallel light in the paraxial region with respect to the optical axis of the projection optical system is made incident from the second object side of the projection optical system and the light in the paraxial region is emergent from the projection optical system), f_{4A} the focal length of the first negative lens (L_{43}) in the intermediate lens group in the fourth lens group G_4, f_{4B} the focal length of the second negative lens (L_{44}) in the intermediate lens group in the fourth lens group G_4, r_{2Ff} the radius of curvature of the first-object-side lens surface of the front lens L_{2F} in the second lens group G_2, r_{2Fr} the radius of curvature of the second-object-side lens surface of the front lens L_{2F} in the second lens group G_2, r_{4N} the radius of curvature of the second-object-side concave surface of the negative lens (L_{44}) in the intermediate lens group in the fourth lens group G_4, r_{4P} the radius of curvature of the first-object-side convex surface of the positive lens (L_{45}) in the intermediate lens group in the fourth lens group G_4, f_{22} the focal length of the second lens with the negative refractive power in the second lens group, f_{23} the focal length of the third lens with the negative refractive power in the second lens group G_2, r_{5n} the radius of curvature of the concave surface in the negative meniscus lens in the fifth lens group G_5, r_{5p} the radius of curvature of the convex surface opposed to the concave surface of the negative meniscus lens in the positive lens disposed as adjacent to the concave surface of the negative meniscus lens in the fifth lens group G_5, r_{5R} the radius of curvature of the second-object-side surface of the negative lens disposed as closest to the second object in the fifth lens group G_5, r_{6F} the radius of curvature of the first-object-side surface of the lens disposed as closest to the first object in the sixth lens group G_6, d_{56} the lens group separation between the fifth lens group G_5 and the sixth lens group G_6, d_6 the axial distance from the lens surface closest to the first object in the sixth lens group G_6 to the second object, r_{5F} the radius of curvature of the first-object-side surface in the negative lens disposed as closest to the second object in the fifth lens group G_5, f_{21} the focal length of the first lens with the positive refractive power in the intermediate lens group G_{2M} in the second lens group G_2, f_{2F} the focal length of the front lens with the negative refractive power disposed as closest to the first object in the second lens group G_2 and shaped with the concave surface to the second object, and f_{2R} the focal length of the rear lens of the negative meniscus shape disposed as closest to the second object in the second lens group G_2 and shaped with the concave surface to the object.

Table 1

First Embodiment

d0 = 94.97557

β = 1/5

NA = 0.57

Bf = 22.68864

L = 1100

	r	d	n
1	758.59372	18.01962	1.66638
2	273.07409	8.00000	
3	407.25600	34.43806	1.53627
4	-305.98082	0.50000	
5	200.00000	36.31512	1.53627
6	-950.89920	0.50000	
7	251.35670	36.00000	1.53627
8	-1111.20100	5.00000	
9	-3000.00000	13.00000	1.66638
10	103.53326	19.34714	
11	583.43731	21.86239	1.53627
12	-202.73262	3.71513	
13	-389.07550	13.00000	1.53627
14	118.39346	25.82991	
15	-119.29984	13.00000	1.53627
16	228.68065	35.35939	
17	-118.78231	15.61439	1.53627

18	-2000.00000	15.00000	
19	-534.21970	30.58806	1.53627
20	-172.96367	0.50000	
21	-3045.95900	30.55054	1.53627
22	-252.31005	0.50000	
23	787.95642	31.33960	1.53627
24	-470.11486	0.50000	
25	429.05519	31.10739	1.53627
26	-1033.56100	0.50000	
27	276.54228	29.82671	1.53627
28	3383.80700	0.50000	
29	200.56082	25.00000	1.53627
30	149.82206	51.17799	
31	191.38232	25.00000	1.53627
32	122.34204	25.15581	
33	-276.65501	13.00000	1.66638
34	-597.90043	9.14516	
35	-190.18194	13.00000	1.66638
36	360.79756	3.75310	
37	434.45763	13.00000	1.53627
38	643.56408	31.17056	
39	-951.39487	20.00000	1.66638
40	360.75541	3.46004	
41	395.41239	33.29191	1.53627
42	-229.24043	0.50000	
43	405.02177	21.76952	1.53627

44	-1456.27300	0.50000	
45	334.62149	34.87065	1.53627
46	-316.02886	8.19653	
47	-226.66975	20.00000	1.66638
48	-421.19119	0.50000	
49	245.00959	27.62592	1.53627
50	-6478.64400	0.50000	
51	118.64887	24.82664	1.53627
52	182.84804	0.50000	
53	106.97354	29.80517	1.53627
54	305.86346	2.86446	
55	330.12685	13.00000	1.66638
56	65.69252	7.67289	
57	76.63392	29.80077	1.53627
58	-405.45793	2.41289	
59	-314.04117	20.42250	1.53627
60	1180.34000	(Bf)	

Table 2

Correspondent Values to the Conditions for First Embodiment
(1) f1/L = 0.129
(2) f2/L = -0.0299
(3) f3/L = 0.106
(4) f4/L = -0.0697
(5) f5/L = 0.0804
(6) f6/L = 0.143
(7) l/L = 2.02
(8) f4A/f4B = 4.24
(9) (r2Ff-r2Fr)/(r2Ff+r2Fr) = 1.07
(10) (r4N-r4P)/(r4N+r4P) = -0.0926
(11) |r4N/L| = 0.328
(12) |r4P/L| = 0.395
(13) f22/f23 = 1.16
(14) (r5p-r5n)/(r5p+r5n) = 0.165
(15) (r5R-r6F)/(r5R+r6F) = -0.0769
(16) d56/L = 0.00698
(17) d6/r6F = 0.983
(18) (r5F-r5R)/(r5F+r5R) = 0.668
(19) f21/L = 0.258
(20) f2F/f2R = 0.635

Table 3

Second Embodiment

d0 = 98.09086

β = 1/5

NA = 0.57

Bf = 22.68864

L = 1100

	r	d	n
1	715.79825	18.01962	1.66638
2	257.11993	8.00000	
3	402.81202	34.43806	1.53627
4	-298.91362	0.50000	

5	200.00000	36.31512	1.53627
6	-811.20841	0.50000	
7	202.30081	36.00000	1.53627
8	-912.77876	-0.24598	
9	-3000.00000	13.00000	1.66638
10	100.16757	19.34714	
11	515.50992	21.86239	1.53627
12	-211.08983	3.71513	
13	-334.85048	13.00000	1.53627
14	119.28367	24.34073	
15	-124.53825	13.00000	1.53627
16	196.56654	35.64064	
17	-122.83913	15.61439	1.53627
18	-2000.00000	15.00000	
19	-319.01403	30.58806	1.53627
20	-192.95790	0.50000	
21	-1320.53000	30.55054	1.53627
22	-229.09627	0.50000	
23	1670.41600	31.33960	1.53627
24	-355.67749	0.50000	
25	505.94351	31.10739	1.53627
26	-669.94239	0.50000	
27	272.78755	29.82671	1.53627
28	-11188.96200	0.50000	
29	205.32433	25.00000	1.53627
30	156.91075	68.35861	

31	170.81860	25.00000	1.53627
32	119.41166	25.17539	
33	-221.51521	13.00000	1.66638
34	3749.27900	7.91441	
35	-299.53056	13.00000	1.66638
36	360.79756	3.75310	
37	434.45763	13.00000	1.53627
38	643.56408	18.53967	
39	-6417.33300	20.00000	1.66638
40	300.16308	3.46004	
41	329.77719	33.29191	1.53627
42	-264.12523	0.50000	
43	804.85248	21.76952	1.53627
44	-784.29788	0.50000	
45	273.73159	34.87065	1.53627
46	-325.58814	8.19653	
47	-214.52517	20.00000	1.66638
48	-405.91293	0.50000	
49	396.09997	27.62592	1.53627
50	-579.80514	0.50000	
51	115.71351	24.82664	1.53627
52	255.34580	0.50000	
53	104.86226	29.80517	1.53627
54	211.50003	2.86446	
55	312.25500	13.00000	1.66638
56	66.11566	7.67289	

57	76.78058	29.80077	1.53627
58	-437.18968	2.41289	
59	-324.32040	20.42250	1.53627
60	2434.44700	(Bf)	

Table 4

Correspondent Values to the Conditions for Second Embodiment
(1) f1/L = 0.119
(2) f2/L = -0.0292
(3) f3/L = 0.111
(4) f4/L = -0.0715
(5) f5/L = 0.0806
(6) f6/L = 0.140
(7) l/L = 2.02
(8) f4A/f4B = 1.29
(9) (r2Ff -r2Fr)/(r2Ff+r2Fr) = 1.07
(10) (r4N-r4P)/(r4N+r4P) = -0.0926
(11) |r4N/L| = 0.328
(12) |r4P/L| = 0.395
(13) f22/f23 = 1.16
(14) (r5p-r5n)/(r5p+r5n) = 0.206
(15) (r5R-r6F)/(r5R+r6F) = -0.114
(16) d56/L = 0.00698
(17) d6/r6F = 0.981
(18) (r5F-r5R)/(r5F+r5R) = 0.673
(19) f21/L = 0.257
(20) f2F/f2R = 0.593

Table 5

Third Embodiment

d 0 = 105.97406

β = 1／5

N A = 0.57

B f = 21.09296

L = 1100

	r	d	n
1	835.93450	19.00074	1.61298
2	349.00002	6.60188	
3	493.73823	30.01023	1.61536
4	-364.99999	1.12825	
5	189.67357	32.71424	1.61536
6	∞	1.25667	
7	219.68925	26.27974	1.61536
8	-2935.50000	2.86486	
9	-1456.03000	15.60000	1.61298
10	98.87901	25.83515	
11	572.77742	19.48735	1.48734
12	-245.99492	3.28431	
13	-517.01308	16.35209	1.61536
14	118.78195	22.95916	
15	-151.83256	12.94478	1.61536
16	196.86505	33.74710	
17	-129.25780	12.89677	1.61536

18	-491.95895	13.46314	
19	-246.12435	22.58245	1.61536
20	-166.51997	0.39125	
21	-1477.30500	28.55306	1.61536
22	-216.04701	0.72991	
23	425.36937	33.51075	1.61536
24	-524.95999	0.96043	
25	438.35798	25.74084	1.48734
26	-1678.66000	0.33363	
27	292.51673	23.69782	1.48734
28	1518.72000	0.83738	
29	218.42396	26.38775	1.48734
30	148.35403	33.09868	
31	203.95726	27.76454	1.61536
32	133.43801	30.67100	
33	-211.86216	13.01538	1.61298
34	-1024.57000	15.53690	
35	-160.75584	13.15020	1.61298
36	270.91502	0.55149	
37	250.92650	15.66663	1.48734
38	702.02996	23.07586	
39	-827.25951	15.36200	1.61298
40	2298.00000	0.73901	
41	2301.62000	27.62162	1.48734
42	-223.08205	0.51051	
43	488.67440	34.23933	1.48734

44	-319.00802	0.49298	
45	500.98379	34.15684	1.61536
46	-369.12909	9.55181	
47	-242.59289	18.84686	1.61298
48	-613.52998	0.50392	
49	347.10206	30.00332	1.61536
50	-1728.40000	0.49017	
51	180.81644	30.27184	1.48734
52	728.32004	0.48766	
53	119.02258	38.20547	1.48734
54	609.84003	3.61782	
55	1650.31000	19.05217	1.61298
56	77.86795	17.17240	
57	81.07073	30.61882	1.48734
58	-335.26499	2.16189	
59	-316.96290	26.15191	1.61536
60	-848.55009	(Bf)	

Table 6

Correspondent Values to the Conditions for Third Embodiment
(1) f1/L = 0.117
(2) f2/L = -0.0288
(3) f3/L = 0.106
(4) f4/L = -0.0762
(5) f5/L = 0.0868
(6) f6/L = 0.147
(7) I/L = 2.87
(8) f4A/f4B = 2.69
(9) (r2Ff-r2Fr)/(r2Ff+r2Fr) = 1.15
(10) (r4N-r4P)/(r4N+r4P) = 0.0383
(11) |r4N/L| = 0.246
(12) |r4P/L| = 0.228
(13) f22/f23 = 1.13
(14) (r5p-r5n)/(r5p+r5n) = 0.207
(15) (r5R-r6F)/(r5R+r6F) = -0.0202
(16) d56/L = 0.0156
(17) d6/r6F = 0.987
(18) (r5F-r5R)/(r5F+r5R) = 0.910
(19) f21/L = 0.324
(20) f2F/f2R = 0.521

Table 7

Fourth Embodiment

d0 = 83.70761

β = 1/5

NA = 0.57

Bf = 21.09296

L = 1100

	r	d	n
1	1185.70800	19.00074	1.61298
2	477.18400	6.60188	
3	1060.88800	30.01023	1.61536
4	-338.64042	1.12825	

5	200.00000	32.71424	1.61536
6	-2276.77900	1.25667	
7	248.82758	26.27974	1.61536
8	-1078.61200	3.19741	
9	-726.49629	15.60000	1.61298
10	110.53957	25.83515	
11	2000.00000	19.48735	1.48734
12	-236.03800	3.28431	
13	-3000.00000	16.35209	1.61536
14	109.86653	32.21675	
15	-153.78948	12.94478	1.61536
16	226.94451	35.22505	
17	-132.31662	12.89677	1.61536
18	-830.43817	15.00000	
19	-330.52996	22.58245	1.61536
20	-184.59786	0.39125	
21	-1874.03800	28.55306	1.61536
22	-221.73570	0.72991	
23	558.10318	33.51075	1.61536
24	-552.83568	0.96043	
25	478.84376	25.74084	1.48734
26	-906.26315	0.33363	
27	287.03514	23.69782	1.48734
28	2359.17900	0.83738	
29	201.46068	26.38775	1.48734
30	155.19710	46.91024	

31	198.66962	27.76454	1.61536
32	122.40099	26.77778	
33	-220.19752	13.01538	1.61298
34	3835.74700	12.87579	
35	-180.57897	13.15020	1.61298
36	270.91501	0.55149	
37	250.92650	15.66663	1.48734
38	702.02997	25.47244	
39	-1387.52600	15.36200	1.61298
40	404.60733	0.73901	
41	437.56855	27.62162	1.48734
42	-242.82524	0.51051	
43	476.89455	34.23933	1.48734
44	-364.55546	0.49298	
45	500.11721	34.15684	1.61536
46	-381.64661	9.55181	
47	-243.22857	18.84686	1.61298
48	-378.77918	0.50392	
49	355.95061	30.00332	1.61536
50	6474.81200	0.49017	
51	171.50098	30.27184	1.48734
52	722.00626	0.48766	
53	113.44841	38.20547	1.48734
54	442.83450	3.61782	
55	730.67537	19.05217	1.61298
56	73.59136	17.17240	

57	78.92998	30.61882	1.48734
58	-315.11137	2.16189	
59	-286.11801	26.15191	1.61536
60	-878.71576	(Bf)	

Table 8

Correspondent Values to the Conditions for Fourth Embodiment
(1) f1/L = 0.119
(2) f2/L = -0.0278
(3) f3/L = 0.106
(4) f4/L = -0.0675
(5) f5/L = 0.0805
(6) f6/L = 0.146
(7) I/L = 2.29
(8) f4A/f4B = 1.94
(9) (r2Ff-r2Fr)/(r2Ff+r2Fr) = 1.36
(10) (r4N-r4P)/(r4N+r4P) = 0.0383
(11) |r4N/L| = 0.246
(12) |r4P/L| = 0.228
(13) f22/f23 = 1.17
(14) (r5p-r5n)/(r5p+r5n) = 0.222
(15) (r5R-r6F)/(r5R+r6F) = -0.0350
(16) d56/L = 0.0156
(17) d6/r6F = 1.01
(18) (r5F-r5R)/(r5F+r5R) = 0.817
(19) f21/L = 0.395
(20) f2F/f2R = 0.603

Letting L be the distance (object-to-image distance) from the object plane P1 (reticle plane) to the image plane P2 (wafer plane) and Φ be a refractive power of lens surface in the sixth lens group G_6, in the first embodiment as described previously, $1/|\Phi L| = 0.130$ for the object-side lens surface of the positive lens L_{61} and $1/|\Phi L| = 0.532$ for the object-side lens surface of the negative lens L_{62}, thus satisfying the condition (21). In the second embodiment, $1/|\Phi L| = 0.130$ for the object-side lens surface of the positive lens L_{61} and $1/|\Phi L| = 0.550$ for the object-side lens surface of the negative lens L_{62}, thus satisfying the condition (21). In the third embodiment, $1/|\Phi L| = 0.151$ for the object-side lens surface of the positive lens L_{61} and $1/|\Phi L| = 0.468$ for the object-side lens surface of the negative lens L_{62}, thus satisfying the condition (21). In the fourth embodiment, $1/|\Phi L| = 0.147$ for the object-side lens surface of the positive lens L_{61} and $1/|\Phi L| = 0.423$ for the object-side lens surface of the negative lens L_{62}, thus satisfying the condition (21).

As described above, the sixth lens group G_6 in each embodiment is composed of three or less lenses including the lens surfaces satisfying the condition (21).

It is understood from the above values of specifications for the respective embodiments that the projection optical systems according to the embodiments achieved satisfactory telecentricity on the object side (reticle R side) and on the image side (wafer W side) as securing the large numerical apertures and wide exposure areas.

Fig. 7 to Fig. 22 are respectively aberration diagrams to show aberrations in the first to fourth embodiments. Each of Figs. 7, 11, 15, and 19 shows a spherical aberration of each embodiment. Each of Figs. 8, 12, 16, and 20 shows an astigmatism of each embodiment. Each of Figs. 9, 13, 17, and 21 shows a distortion of each embodiment. Each of Figs. 10, 14, 18, and 22 shows a coma of each embodiment.

Here, in each aberration diagram, NA represents the numerical aperture of the projection optical system 1, and Y the image height, and in each astigmatism diagram, the dashed line represents the meridional image surface and the solid line the sagittal image surface.

It is understood from comparison of the aberration diagrams that the aberrations are corrected in a good balance in each embodiment even with a wide exposure area (image height) and a large numerical aperture, particularly, distortion is extremely well corrected up to nearly zero throughout the entire image, thus achieving the projection optical system with high resolving power in a wide exposure area.

The above-described embodiments showed the examples using the mercury lamp as a light source for supplying the exposure light of the i-line (365 nm), but it is needless to mention that the invention is not limited to the examples; for example, the invention may employ light sources including a mercury lamp supplying the exposure light of the g-line (435 nm), and extreme ultraviolet light sources such as excimer lasers supplying light of 193 nm or 248 nm.

In the above each embodiment the lenses constituting the projection optical system are not cemented to each other, which can avoid a problem of a change of cemented surfaces with time. Although in the above each embodiment the lenses constituting the projection optical system are made of a plurality of optic materials, they may be made of a single glass material, for example quartz (SiO_2) if the wavelength region of the light source is not a wide band.

As described above, the projection optical system according to the present invention can achieve the bitelecentricity in a compact design as securing a wide exposure area and a large numerical aperture, and the invention can achieve the projection optical system with high resolving power corrected in a good balance for aberrations, particularly extremely well corrected for distortion.

From the invention thus described, it will be obvious that the invention may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims. The basic Japanese Application No. 872/1995 filed on January 6, 1995 is hereby incorporated by reference.

Claims

1. A projection optical system provided between a first objects and a second object, for projecting an image of a first object onto a second object, said projection optical system comprising a first lens group with a positive refracting power, a second lens group with a negative refracting power, a third lens group with a positive refracting power, a fourth lens group with a negative refracting power, a fifth lens group with a positive refracting power, and a sixth lens group with a positive refracting power in order from the side of said first object,

   wherein said second lens group comprises a front lens with a negative refracting power disposed as closest to said first object and shaped with a concave surface to said second object, a rear lens of a negative meniscus shape disposed as closest to said second object and shaped with a concave surface to said first object, and an intermediate lens group disposed between said front lens and said rear lens, said intermediate lens group having a first lens with a positive refracting power, a second lens with a negative refracting power, and a third lens with a negative refracting power in order from the side of said first object, and

   wherein when f_1 is a focal length of said first lens group, f_2 is a focal length of said second lens group, f_3 is a focal length of said third lens group, f_4 is a focal length of said fourth lens group, f_5 is a focal length of said fifth lens group, f_6 is a focal length of said sixth lens group, and L is a distance from said first object to said second object, the following conditions are satisfied:

$$f_1/L < 0.8$$

$$-0.033 < f_2/L$$

$$0.01 < f_3/L < 1.0$$

$$f_4/L < -0.005$$

$$0.01 < f_5/L < 0.9$$

$$0.02 < f_6/L < 1.6.$$

2. A projection optical system according to claim 1, wherein when l is an axial distance from said first object to a first-object-side focal point of said entire projection optical system and L is the distance from said first object to said second object, the following condition is satisfied:

$$1.0 < l/L$$

3. A projection optical system according to claim 1, wherein said fourth lens group comprises:
   a front lens group disposed as closest to the first object, said front lens group having two negative meniscus lenses each shaped with a concave surface to said second object;
   a rear lens group disposed as closest to the second object, said rear lens group having a negative lens with a concave surface to said first object; and
   an intermediate lens group disposed between said front lens group in said fourth lens group and said rear lens group in said fourth lens group, said intermediate lens group having first and second negative lenses in order from the side of said first object, and
   wherein when f_{4A} is a focal length of said first negative lens in said fourth lens group and f_{4B} is a focal length of said second negative lens in said fourth lens group, the following condition is satisfied:

$$0.05 < f_{4A}/f_{4B} < 20.$$

4. A projection optical system according to claim 1, wherein when F_{2Ff} is a radius of curvature of a first-object-side surface of said front lens and r_{2Fr} is a radius of curvature of a second-object-side surface of said front lens, the front lens in said second lens group satisfies the following condition:

$$1.00 \leq (r_{2Ff} - r_{2Fr})/(r_{2Ff} + r_{2Fr}) < 5.0.$$

5. A projection optical system according to claim 1, wherein said fourth lens group has:
   a front lens group having a negative lens disposed as closest to said first object and shaped with a concave surface to said second object;
   a rear lens group having a negative lens disposed as closest to the second object and shaped with a concave surface to said first object; and
   an intermediate lens group having a negative lens and a positive lens with a convex surface adjacent to a concave surface of said negative lens is disposed between said front lens group in said fourth lens group and said rear lens group in said fourth lens group, and
   wherein when r_{4N} is a radius of curvature of said concave surface of the negative lens in said intermediate lens group and r_{4P} is a radius of curvature of said convex surface of the positive lens in said intermediate lens group, the following condition is satisfied:

$$-0.9 < (r_{4N} - r_{4P})/(r_{4N} + r_{4P}) < 0.9,$$

   provided that when L is the distance from said first object to said second object, said concave surface of said negative lens in said intermediate lens group or said convex surface of said positive lens in said intermediate lens group satisfies at least one of the following conditions:

$$|r_{4N}/L| < 2.0$$

$$|r_{4P}/L| < 2.0.$$

6. A projection optical system according to claim 1, wherein when f_{22} is a focal length of the second lens with the negative refracting power in said second lens group and f_{23} is a focal length of the third lens with the negative refracting power in said second lens group, the following condition is satisfied:

$$0.1 < f_{22}/f_{23} < 10.$$

7. A projection optical system according to claim 1, wherein said fifth lens group has a negative meniscus lens, and a positive lens disposed as adjacent to a concave surface of said negative meniscus lens and having a convex surface opposed to the concave surface of said negative meniscus lens, and

wherein when r_{5n} is a radius of curvature of the concave surface of said negative meniscus lens in said fifth lens group and r_{5P} is a radius of curvature of the convex surface, opposed to the concave surface of the negative meniscus lens, of the positive lens disposed as adjacent to the concave surface of said negative meniscus lens in said fifth lens group, the following condition is satisfied:

$$0 < (r_{5P} - r_{5n})/(r_{5P} + r_{5n}) < 1.$$

8. A projection optical system according to claim 7, wherein said negative meniscus lens and said positive lens adjacent to the concave surface of said negative meniscus lens are disposed between at least one positive lens in said fifth lens group and at least one positive lens in said fifth lens group.

9. A projection optical system according to claim 1, wherein said fifth lens group has a negative lens disposed as closest to the second object and shaped with a concave surface to the second object and the sixth lens group has a lens disposed as closest to the first object and shaped with a convex surface to the first object, and

wherein when r_{5R} is a radius of curvature of a second-object-side surface of the negative lens disposed as closest to the second object in said fifth lens group and r_{6F} is a radius of curvature of a first-object-side surface of the lens disposed as closest to the first object in said sixth lens group, the following condition is satisfied:

$$-0.90 < (r_{5R} - r_{6F})/(r_{5R} + r_{6F}) < -0.001.$$

10. A projection optical system according to claim 1, wherein when d_{56} is a lens group separation between said fifth lens group and said sixth lens group and L is the distance from said first object to said second object, the following condition is satisfied:

$$d_{56}/L < 0.017.$$

11. A projection optical system according to claim 1, wherein when r_{6F} is a radius of curvature of a lens surface closest to the first object in said sixth lens group and d_6 is an axial distance from the lens surface closest to the first object in said sixth lens group to the second object, the following condition is satisfied:

$$0.50 < d_6/r_{6F} < 1.50.$$

12. A projection optical system according to claim 1, wherein said fifth lens group has a negative lens disposed as closest to the second object and shaped with a concave surface to the second object, and wherein when r_{5F} is a radius of curvature of a first-object-side surface of the negative lens disposed as closest to the second object in said fifth lens group and r_{5R} is a radius of curvature of a second-object-side surface of the negative lens disposed as closest to the second object in said fifth lens group, the following condition is satisfied:

$$0.30 < (r_{5F} - r_{5R})/(r_{5F} + r_{5R}) < 1.28.$$

13. A projection optical system according to claim 1, wherein when f_{21} is a focal length of the first lens with the positive refracting power in the intermediate lens group in said second lens group and L is the distance from said first object to said second object, the following condition is satisfied:

$$0.230 < f_{21}/L < 0.40.$$

14. A projection optical system according to claim 1, wherein when f_{2F} is a focal length of the front lens with the negative refracting power disposed as closest to the first object in said second lens group and shaped with the concave surface to said second object and f_{2R} is a focal length of the rear lens with the negative refracting power disposed as closest to the second object in said second lens group and shaped with the concave surface to said first object, the following condition is satisfied:

$$0 \leq f_{2F}/f_{2R} < 18.$$

15. A projection optical system according to claim 1, wherein the intermediate lens group in said second lens group has a negative refracting power.

16. A projection optical system according to claim 1, wherein said first lens group has at least two positive lenses, said third lens group has at least three positive lenses, said fourth lens group has at least three negative lenses, said fifth lens group has at least five positive lenses and at least one negative lens, and said sixth lens group has at least one positive lens.

17. A projection optical system according to claim 1, wherein said sixth lens group comprises three or less lenses having at least one lens surface satisfying the following condition:

$$1/|\Phi L| < 20$$

where Φ: a refractive power of said lens surface, and
L: the object-to-image distance from said first object to said second object.

18. A projection optical system according to claim 1, wherein a magnification of said projection optical system is 1/5.

19. An exposure apparatus comprising:
a stage allowing a photosensitive substrate to be held on a main surface thereof;
an illumination optical system for emitting exposure light of a predetermined wavelength and transferring a predetermined pattern of a mask onto said substrate; and
a projection optical system provided between said mask and said substrate, said projection optical system including a first lens group with a positive refracting power, a second lens group with a negative refracting power, a third lens group with a positive refracting power, a fourth lens group with a negative refracting power, a fifth lens group with a positive refracting power, and a sixth lens group with a positive refracting power in order from the side of said mask,
wherein said second lens group comprises a front lens with a negative refracting power disposed as closest to said first object and shaped with a concave surface to said second object, a rear lens of a negative meniscus shape disposed as closest to said second object and shaped with a concave surface to said mask, and an intermediate lens group disposed between said front lens and said rear lens, said intermediate lens group having a first lens with a positive refracting power, a second lens with a negative refracting power, and a third lens with a negative refracting power in order from the side of said mask, and
wherein when f_1 is a focal length of said first lens group, f_2 is a focal length of said second lens group, f_3 is a focal length of said third lens group, f_4 is a focal length of said fourth lens group, f_5 is a focal length of said fifth lens group, f_6 is a focal length of said sixth lens group, and L is a distance from said mask to said substrate, the following conditions are satisfied:

$$f_1/L < 0.8$$

$$-0.033 < f_2/L$$

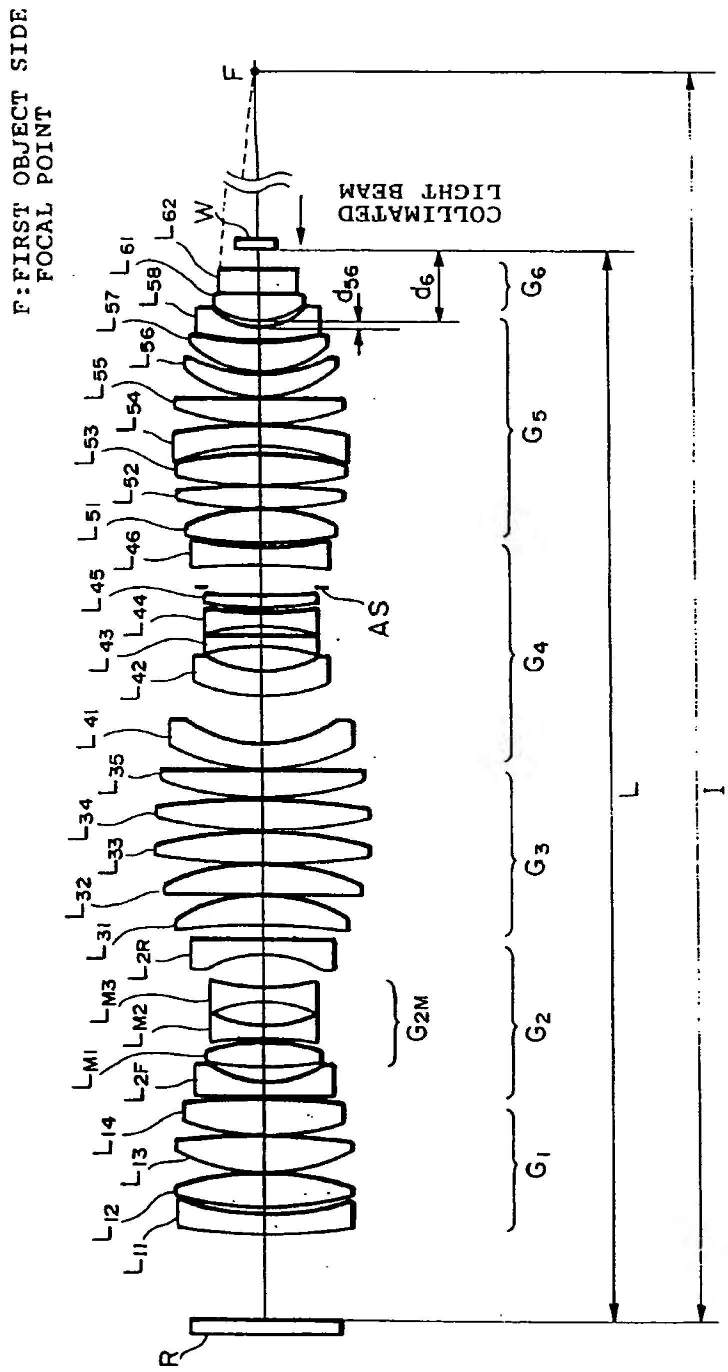
$$0.01 < f_3/L < 1.0$$

$$f_4/L < -0.005$$

$$0.01 < f_5/L < 0.9$$

$$0.02 < f_6/L < 1.6.$$

20. An exposure apparatus according to claim 19, wherein a magnification of said projection optical system is 1/5.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COLLIMATED
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L_{2F}
L_{14}
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L_{12}
L_{11}
R
AS
d_{56}
d_6
G_6
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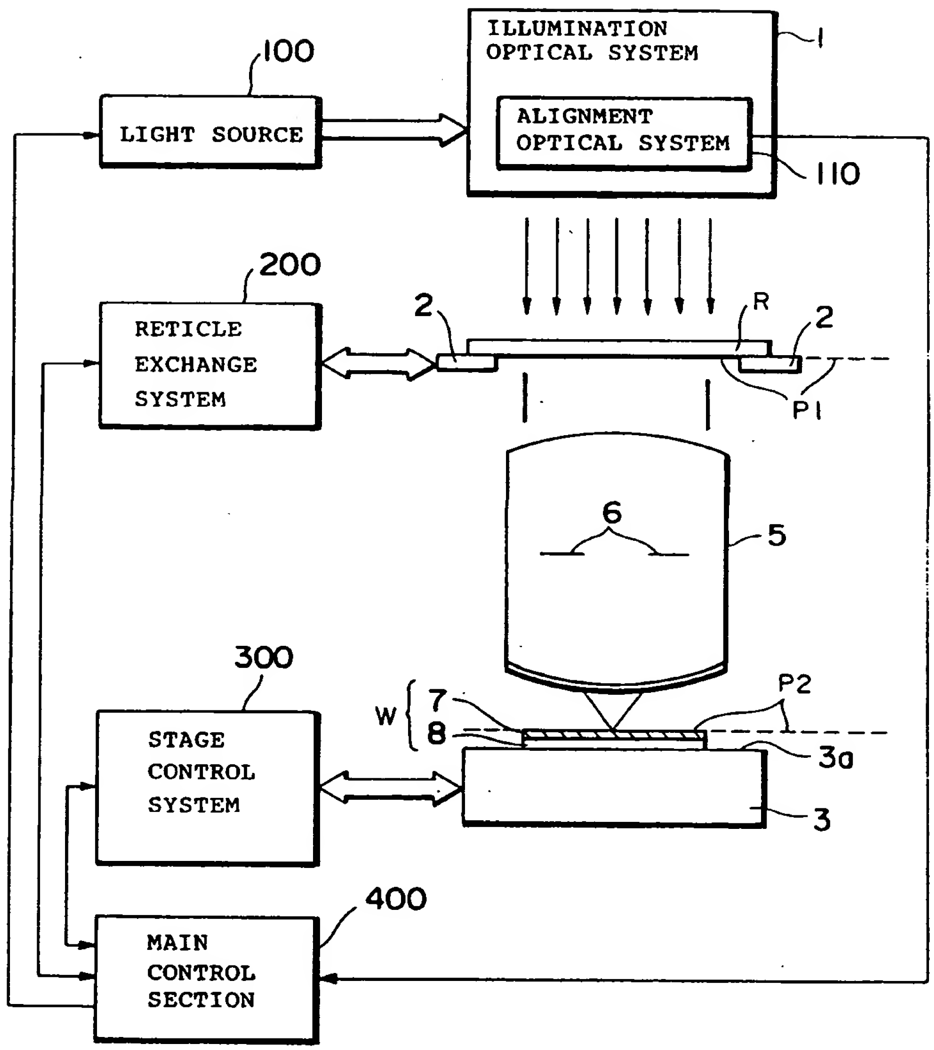
G_1
L
I

Fig. 1

Fig. 2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RETICLE EXCHANGE SYSTEM
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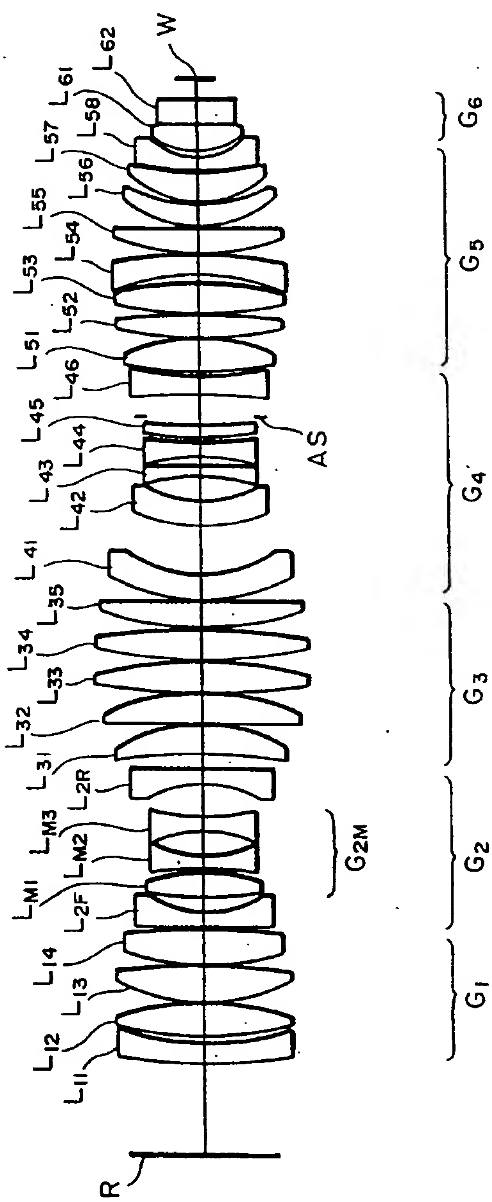
300
P2
W
7
8
3a
STAGE CONTROL SYSTEM
3
400
MAIN CONTROL SECTION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W
AS
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L12
L13
L14
L2F
LM1
LM2
LM3
L2R
L31
L32
L33
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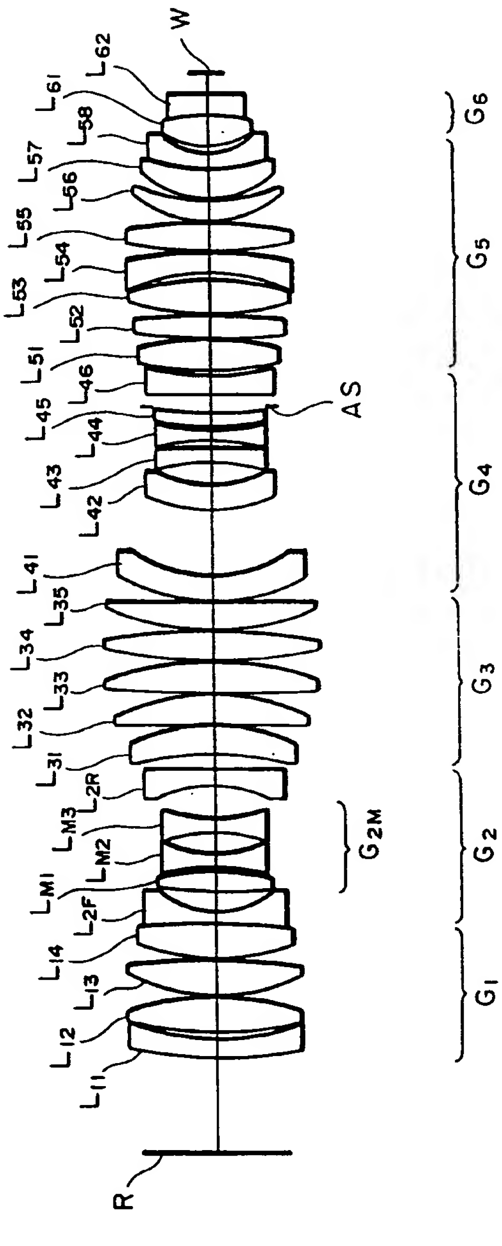
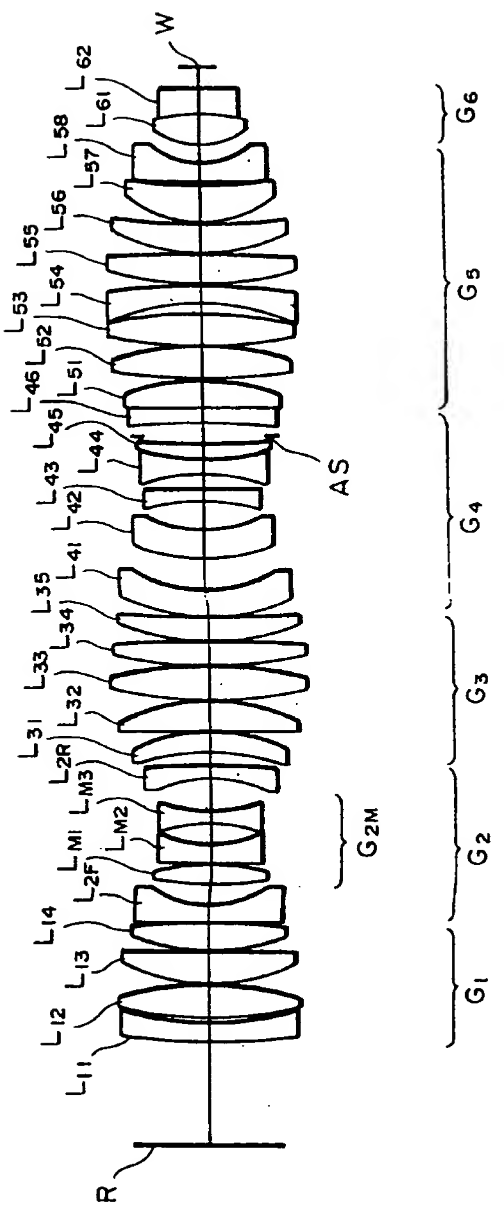
L35
L41
L42
L43
L44
L45
L46
L51
L52
L53
L54
L55
L56
L57
L58
L61
L62
G1
G2
G2M
G3
G4
G5
G6

Fig. 3

Fig. 4


W
R
AS
G1
G2
G2M
G3
G4
G5
G6
L11
L12
L13
L14
L2F
LM1
LM2
LM3
L2R
L31
L32
L33
L34
L35
L41
L42
L43
L44
L45
L46
L51
L52
L53
L54
L55
L56
L57
L58
L61
L62


W
L62
L61
L58
L57
L56
L55
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L53
L52
L46
L51
L45
L44
AS
L43
L42
L41
L35
L34
L33
L32
L31
L2R
LM3
LM2
LM1
L2F
L14
L13
L12
L11
R
G6
G5
G4
G3
G2
G2M
G1

Fig. 5

Fig. 6

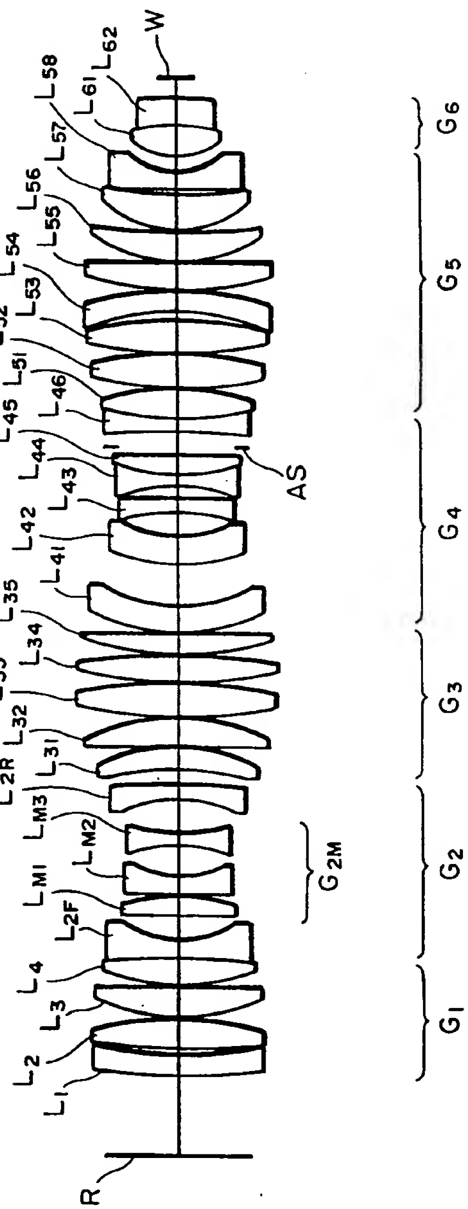

R
W
AS
L_1
L_2
L_3
L_4
L_{2F}
L_{M1}
L_{M2}
L_{M3}
L_{2R}
L_{31}
L_{32}
L_{33}
L_{34}
L_{35}
L_{41}
L_{42}
L_{43}
L_{44}
L_{45}
L_{46}
L_{51}
L_{52}
L_{53}
L_{54}
L_{55}
L_{56}
L_{57}
L_{58}
L_{61}
L_{62}
G_1
G_2
G_{2M}
G_3
G_4
G_5
G_6

Fig.10

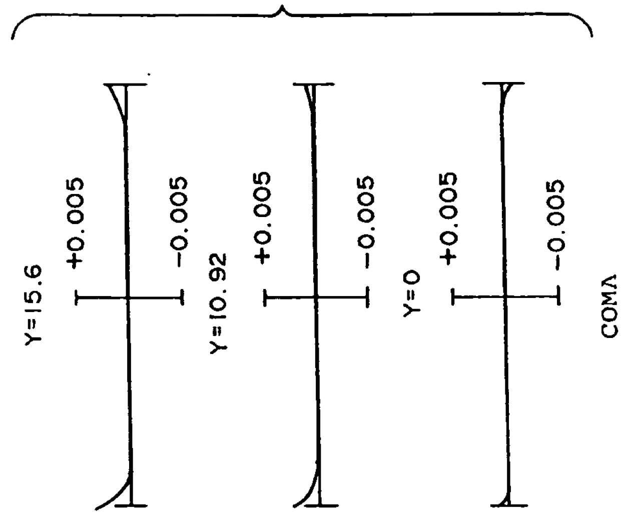


Fig.9

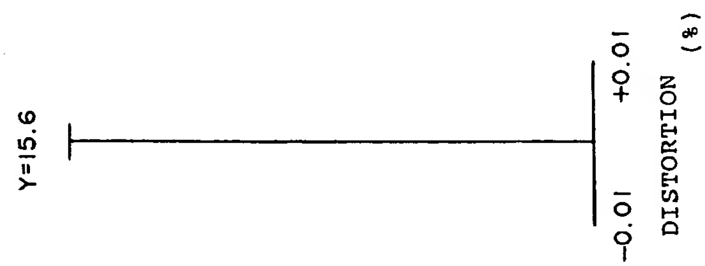


Fig.8

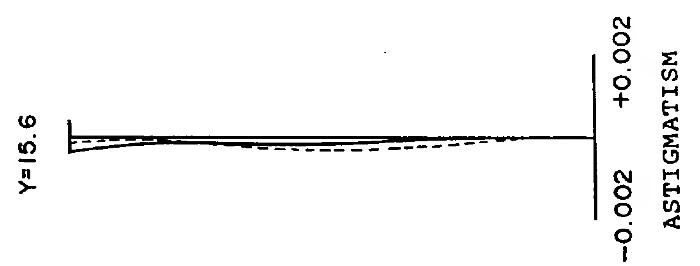
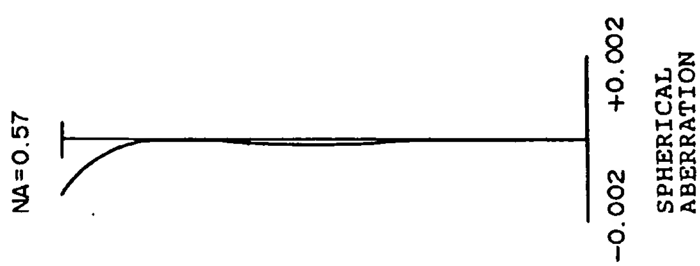


Fig.7



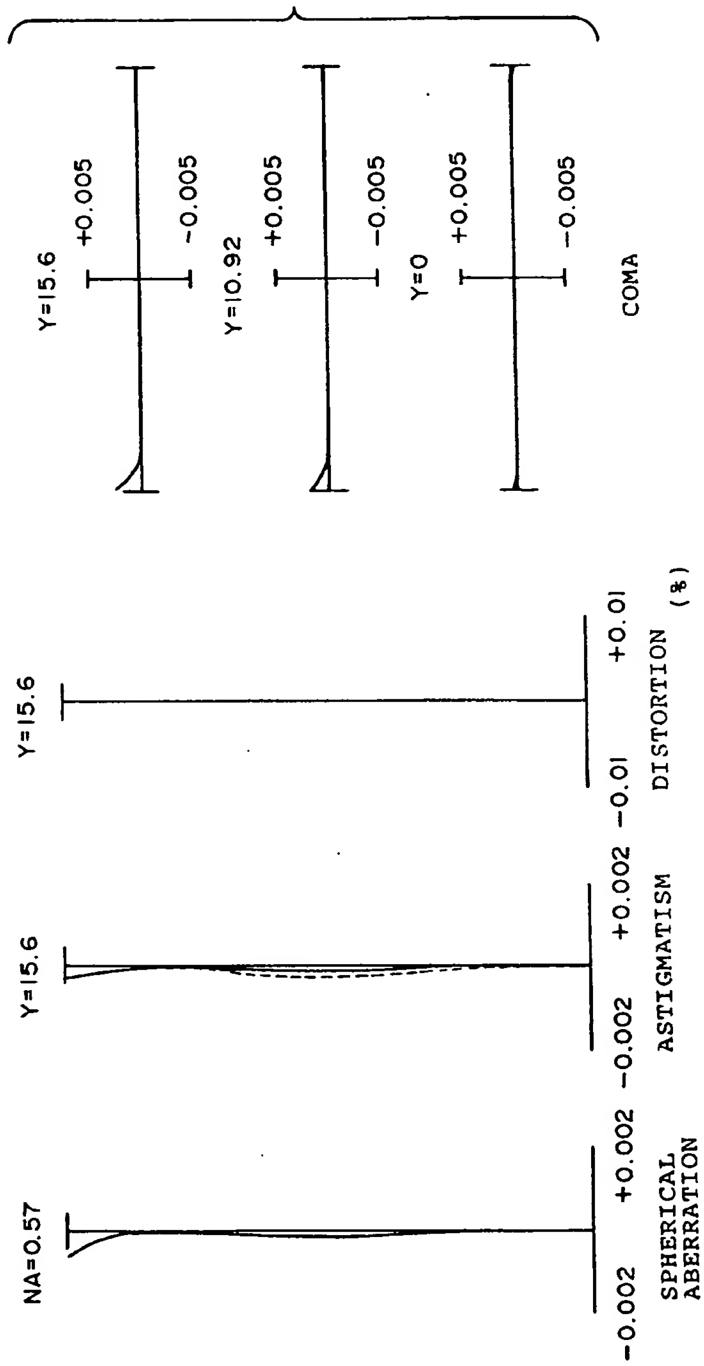


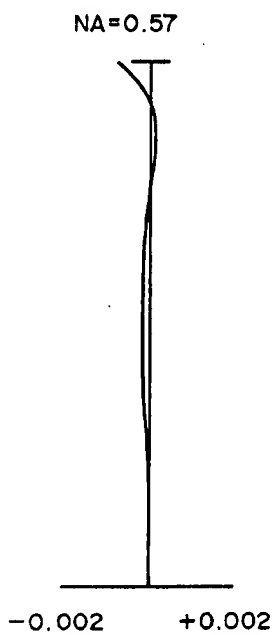
Fig.11

Fig.12

Fig.13

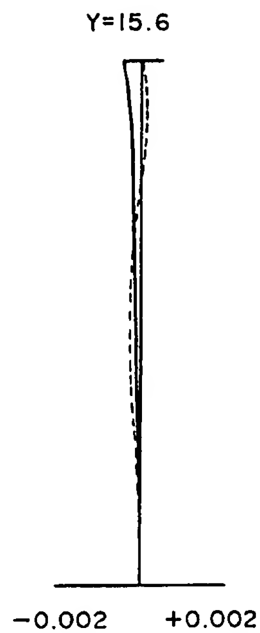
Fig.14

Fig.15



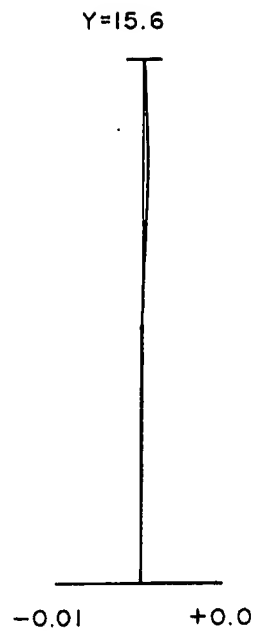
SPHERICAL ABERRATION

Fig.16



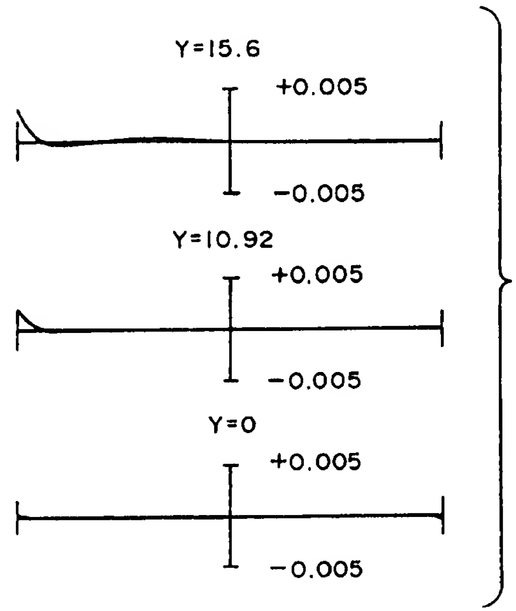
ASTIGMATISM

Fig.17



DISTORTION (%)

Fig.18



COMA

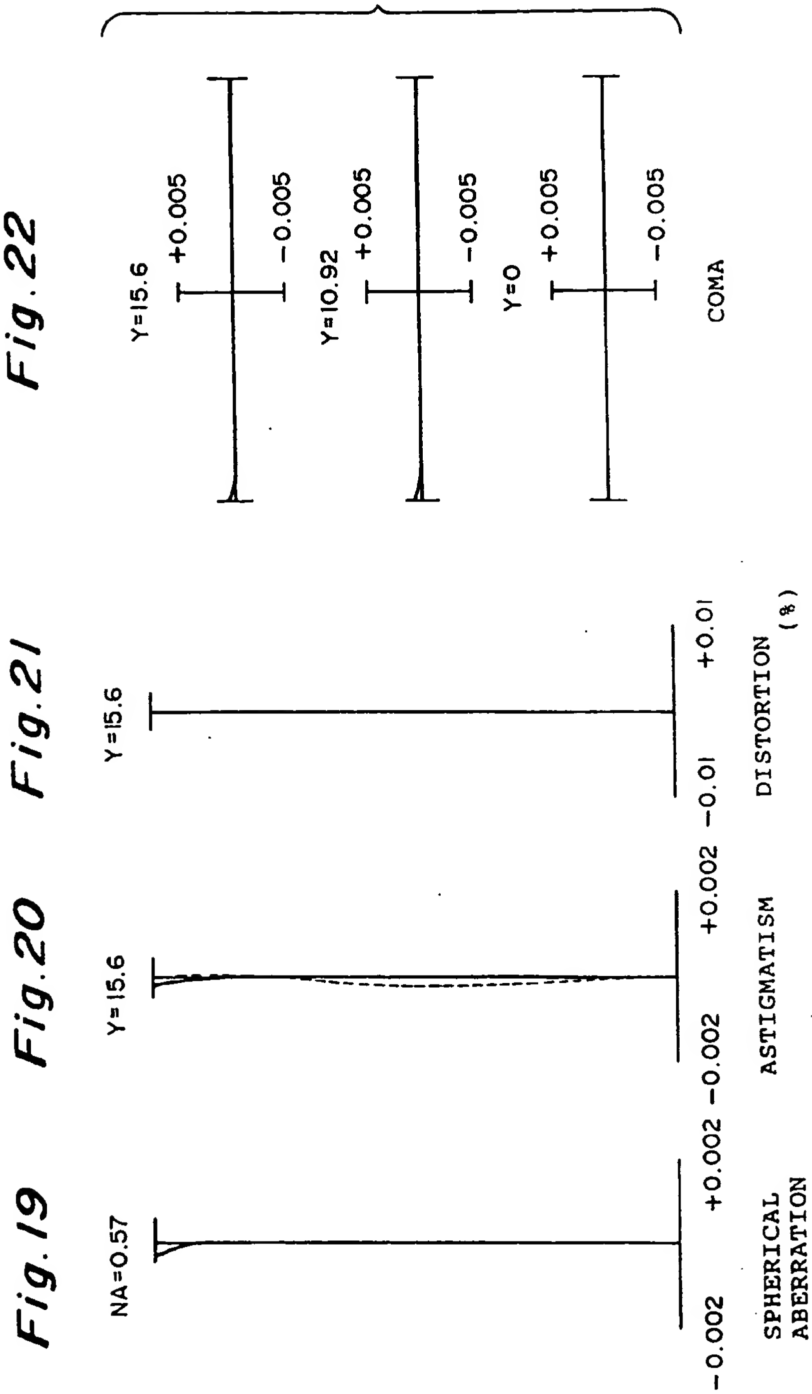


Fig.19

Fig.20

Fig.21

Fig.22